Ontario

Ministry of Transportation
Geomatics Office Report

High Accuracy Photogrammetric Mapping from Large Scale Aerial Photography

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Abstract	The focus of this study was to examine the potential of using large scale aerial photography taken by low-flying helicopter to provide a high-accuracy photogrammetric mapping product suitable for detailed engineering design. Results indicate that the helicopter methodology can support pavement data collection accurate to 2 centimetres. Some features (i.e. earth ditches, culverts, inverts) may still require ground survey to supplement the photogrammetric mapping. Using this technology reduces the need for expensive and inconvenient traffic protection measures such as lane closures and use of blocker trucks, reducing traffic congestion and traffic control costs. Ground survey accuracy can be achieved without sending surveyors onto the traveled lanes, reducing field crew exposure to heavy traffic, thereby providing a safer, more efficient way of collecting the critical pavement data.

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Executive Summary

The Geomatics Office of the Ontario Ministry of Transportation is continuously examining ways to improve the collection of pavement data and other topographic detail on provincial highways. This data is required for planning and designing new construction, reconstruction, lane additions and pavement resurfacing.

Collecting accurate pavement data on busy highways is dangerous to surveyors and disruptive to the motoring public. Surveyors must venture onto live lanes during breaks in traffic, or set up extensive traffic control and lane closures. Due to these safety issues and traffic control problems, critical pavement data is not collected on many projects. In fact, no pavement data is collected between the outer edges of pavement on most surveys of major highways in the Greater Toronto Area (GTA). On a major highway such as Highway 401, a data void will exist on the traveled surface and designers must make assumptions about the location of the crown of the road, crossfall, drainage patterns, etc.

The Geomatics Office has been investigating numerous emerging technologies in an effort to find practical, safe, cost-effective solutions for surveying pavement. Examples include reflectorless total stations, lidar (airborne and terrestrial), satellite imagery, and mobile road profiling (by Ministry-owned ARAN vehicles).

The focus of this study was to examine the potential of using large scale aerial photography taken by low-flying helicopter to provide a high-accuracy photogrammetric mapping product suitable for detailed engineering design. Results indicate that the helicopter methodology can support pavement data collection accurate to 2 centimetres, as required by MTO's Standards for Engineering Surveys (1998). Some features (i.e. earth ditches, culverts, inverts) may still require ground survey to supplement the photogrammetric mapping.

Using this technology reduces the need for expensive and inconvenient traffic protection measures such as lane closures and use of blocker trucks, reducing traffic congestion and traffic control costs. Ground survey accuracy can be achieved without sending surveyors onto the traveled lanes, reducing field crew exposure to heavy traffic, thereby providing a safer, more efficient way of collecting the critical pavement data. A better digital terrain model (DTM) can be provided to designers since a much higher density of data points can be collected more efficiently by photogrammetric methods than by ground surveying. The initial increased mapping cost will be offset by savings in the construction phase, since a more accurate survey will lead to a better design, thereby reducing construction overruns.

High accuracy photogrammetric mapping should be considered for high-volume traffic areas where major traffic control and lane closures would be required for ground surveys, field

crews would be at risk to carry out survey operations safely, or minimal disruption to traffic is required. Other applications include areas that are inaccessible or impractical to survey by ground methods (i.e. ramps, interchanges, multi-level structures, bridges) and areas with severe survey restrictions imposed (i.e. survey work can only be conducted at night). The technique should also be considered when pavement data collected by ground survey is not sufficient to produce an accurate digital terrain model. For example, in instances when no survey data is collected between the edges of pavement, critical parameters s such as the crown elevation and crossfall must be estimated.

Introduction

Working safely on provincial highways is an ongoing concern at the Ontario Ministry of Transportation (MTO). The ministry's Geomatics Office is continually looking for ways to survey pavement and other topographic detail accurately without sending survey crews onto the highway, closing lanes, using blocker trucks, etc. This data is required for planning and designing new construction, reconstruction, lane additions, and pavement resurfacing. This report focuses on a pilot project undertaken to attempt high-accuracy photogrammetric mapping by acquiring aerial photography along a highway corridor from a helicopter flying at very low altitudes. This method of obtaining pavement data has the potential to achieve ground survey accuracy from the air, thereby providing for a safer, more efficient way of collecting this critical data.

In May 2001, a Bell Jet Ranger Helicopter was flown over Highway 62 North in Bancroft for 7 kilometres, at an altitude of approximately 90 metres. The helicopter was fitted with an aerial camera designed specifically for acquiring aerial photography at very low altitudes. The Bancroft site was chosen because the low traffic flow would allow for extensive ground truthing and accuracy assessment on a full range of hard and soft surface features. During the pilot, drivers were advised of the low altitude flight pattern through changeable message signs set up along the highway test area.

The study was conducted to:

- Examine the possibility of achieving MTO's engineering survey accuracy requirements on pavement using airborne photogrammetric techniques.
- Investigate an alternative survey method that may increase safety to surveyors by minimizing their contact with live lanes of traffic.
- Investigate an alternative survey method that may minimize disruption to the travelling public by reducing lane closures and use of blocker trucks.

It was recognized that using proven photogrammetric mapping methodology, but drastically increasing the scale of photography by flying at a much lower altitude, could potentially provide engineering survey accuracy on pavement using airborne techniques. A helicopter would be needed, instead of a fixed wing aircraft, to safely fly at the low altitudes.

Traditionally, MTO acquires aerial photography flown at an altitude of approximately 450 metres resulting in a photo scale of 1:3000, and accurate to within 10 centimetres. The photogrammetric mapping information is then supplemented with ground survey data to obtain the final required accuracy of 2 centimetres on pavement. In the case of high-accuracy photogrammetric mapping, a helicopter flies at an altitude of 90 metres, acquiring photography at a scale of 1:600. This represents a five-time increase in photo

scale. The subsequent mapping can theoretically increase in accuracy by a factor of 5, with a resulting theoretical accuracy of 2 centimetres. As this is the desired final accuracy, supplementary ground survey data collection is greatly reduced, thereby improving the safety and efficiency of pavement data collection.

High-accuracy photogrammetric mapping reduces safety risks and the lane closures that are needed when obtaining pavement data by ground survey methods. Normally, crews have to work within live traffic lanes while conducting ground surveys, thus lane closures and blocker trucks are required. With an aerial-only method for obtaining pavement data, highway safety and functionality is improved for both drivers and workers.

This proposed methodology could have profound effects on pavement data collection. Survey crews would not have to enter the live lanes. They would be able to limit their activities to establishing control points off the traveled portion of the highway. Lane closures and use of blocker trucks would be minimized or potentially eliminated. As a result, worker and driver safety would be improved.

Favourable results have been reported on similar projects conducted for transportation departments in the United States. Thus an extensive study of the technology was undertaken by MTO to verify the methodology and determine the achievable accuracy.

Typical MTO Surveying Approach

MTO has been acquiring aerial photography and performing photogrammetric mapping since the 1950's. Equipment has evolved from mechanical instruments and hardcopy photographs to fully digital environments using computers and scanned images. However the theory and methodology of photogrammetric measurement has not changed, thus photogrammetry is a well-established survey technique. The accuracy of the photogrammetric product is primarily dependent on the measurement precision of the equipment and the scale of the photography. The scale of photography is directly proportional to the flying height at the time of exposure. A lower flying height produces larger scale photography, which can be mapped more accurately.

Traditionally, MTO acquires aerial photography flown at an altitude of approximately 450 metres resulting in a photo scale of 1:3000. Accuracy requirements for feature collection are based on the scale of photography and the specifications for photo measurement accuracy in digitizing units (micrometres or 10^{-6} metres):

Ground accuracy (metres) = photo measurement accuracy * photo scale number (1)

For hard surface features (i.e. crown, edge of pavement, curb, sidewalk) the required photo measurement accuracy is 30 micrometres, resulting in a ground accuracy of ($30 \times 10^{-6} \times 3000$) = 0.09m for 1:3000 scale photography. For soft surface features (i.e. natural ground, ditches) the required measurement accuracy is 75 micrometres, or a ground accuracy of ($75 \times 10^{-6} \times 3000$) = 0.23m (Ministry of Transportation Ontario, 1994).

Photogrammetric mapping has certain advantages over ground surveying:

- Ground work is minimized. Once photogrammetric control points have been surveyed by traditional ground survey methods, no further ground contact is required.
- Surveyors' exposure to traffic hazards is minimized.
- Traffic disruptions, lane closures and use of blocker trucks are minimized.
- All visible terrain features can be mapped safely from the photography.
- Large quantities of data can be collected more economically.

Unfortunately, 9 cm accuracy on hard surface features is not accurate enough for detailed design. Therefore the photogrammetric mapping must be supplemented with ground survey data collected by total station or GPS to obtain the final required accuracy of 2 centimetres on pavement. Since the ground survey is required on live traffic lanes, many of the benefits of photogrammetric mapping are eliminated. Safety concerns and traffic disruptions continue to plague MTO mapping projects.

TRAFFIC CONTROL RESTRICTIONS ON MAJOR HIGHWAYS

Traffic control restrictions can have a major impact on roadwork conducted on provincial highways. On Ontario's 400-series highways, lane closures and use of blocker trucks are usually required for any roadwork conducted within three metres of traveled lanes (Ministry of Transportation Ontario, 2001). In very busy areas it is not practical to survey the pavement except on the outer edges (edge of pavement shots). Some areas cannot be surveyed at all i.e. major on- or off-ramps. Thus design often proceeds without important survey information and assumptions must be made about certain critical features such as crown elevation and crossfall.

In locations such as the Greater Toronto Area and Ottawa area there are many additional traffic control conditions. The MTO Traffic Office must be contacted to determine permitted hours for lane closures. The time and duration of the closure is determined by factors such as: traffic volume; location of the survey relative to on- and off-ramps; location of other construction and maintenance activities; number of existing lanes; and time of day.

Permitted working hours will also vary with location:

- Along lower volume major routes (i.e. highways 400 or 404 north of Toronto, highway 417 through Ottawa) permitted working hours are about 9am - 3pm.
- Along busier major routes (i.e. highway 403 between QEW and 401) permitted working hours are about 10am to 2pm.
- Along high volume major routes (i.e. QEW from Burlington easterly, highways 427 and 401 through Toronto) only night surveys are permitted.
- Bridge ramps such as the highway 400/401 interchange may not be allowed any type of normal closing (i.e. police presence may be required).

Similar conditions apply for the use of blocker trucks. Blocker trucks cost $1,000 to $1,500 per day. Even when blocker trucks are called, roadwork may not be permitted if conditions are deemed to be unsafe. Thus reduction of ground survey work is highly desirable on major highways.

Helicopter Surveying Approach

The helicopter survey approach is similar to typical MTO photogrammetric mapping projects since aerial photography is acquired, ground control and photo-identifiable points are surveyed, aerial triangulation is performed and physical features are mapped by photogrammetric methods. The key difference is the scale of photography used.

In the case of high-accuracy photogrammetric mapping, the helicopter flies at an altitude of 90 metres above the terrain, acquiring photography at a scale of 1:600. This represents a five-time increase in scale over typical MTO photography (1:600 versus 1:3000, see Figure 1), with a resulting theoretical accuracy of less than 2 centimetres.

A helicopter can safely fly at low altitudes, whereas fixed-wing aircraft are generally restricted to flying above 300 metres. Also, for 1:600 photography a photo must be taken every 55 metres, thus the helicopter must fly slow enough to allow the aerial camera to capture photographs at this high exposure rate. Most fixed-wing aircraft cannot safely fly slowly enough for the required camera exposure cycle.

The photo measurement accuracy specifications for this project were the same as for any other photogrammetric mapping project conducted by MTO, that is 30 and 75 micrometres for hard and soft surfaces, respectively (see previous section). Therefore using Equation 1 for 1:600 scale photography, the required accuracy for hard surface features is $(30 \times 10^{-6} \times 600) = 0.018$m and the required accuracy for soft surface features is $(75 \times 10^{-6} \times 600) = 0.045$m.

If this accuracy is achievable, the resultant photogrammetric mapping would meet the survey requirements for detailed design, and supplementary ground survey data collection would be greatly reduced or eliminated. There would be less traffic disruption and less safety risk for surveyors. Data not normally collected on busy highways (i.e. crown shots) would be available to the designer.

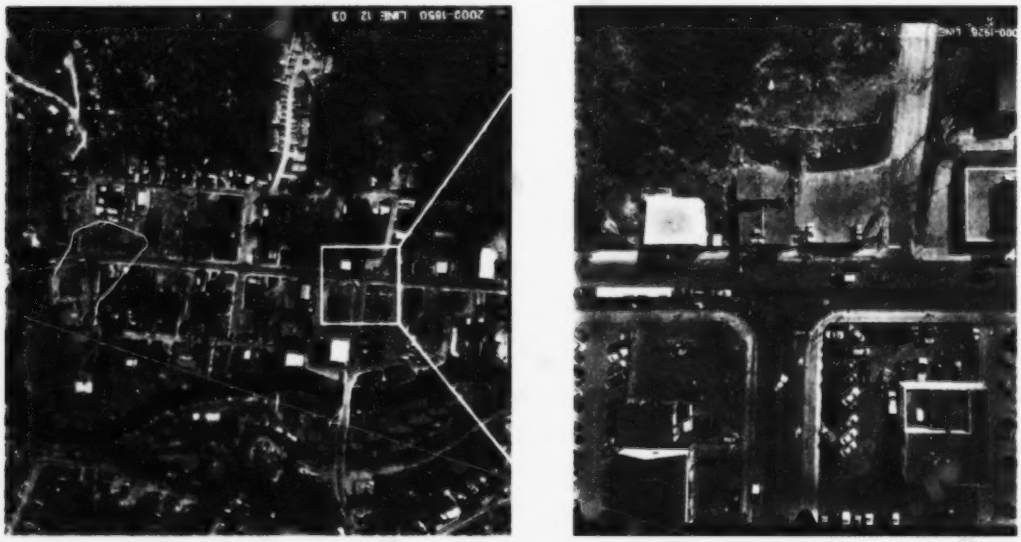

Figure 1 - 1:3000 photo (left) and 1:600 photo (right)

Pilot Project: Highway 62 Bancroft

PROJECT AREA

The pilot project was conducted on Highway 62, beginning in the Town of Bancroft at the intersection of Highways 62 and 28, going northerly for approximately 7 kilometres to Bird's Creek. See Figure 2.

Highway 62 is a 2-lane King's highway. The project area is an urban setting through Bancroft for the first couple kilometres characterized by paved entrances to numerous residential and commercial buildings, curbs, sidewalks, etc. The setting changes to semi-rural for the remaining five kilometres with low-density housing, earth ditches, and natural areas. The elevation changes by about 15m from one end to the other.

A number of practical considerations influenced selection of the Bancroft pilot site, including; low traffic flow to allow for extensive ground survey audits; full range of hard and soft surface features for accuracy assessment; recent reconstruction so pavement conditions would not change in the near future; and the photogrammetric mapping was needed for future capital construction.

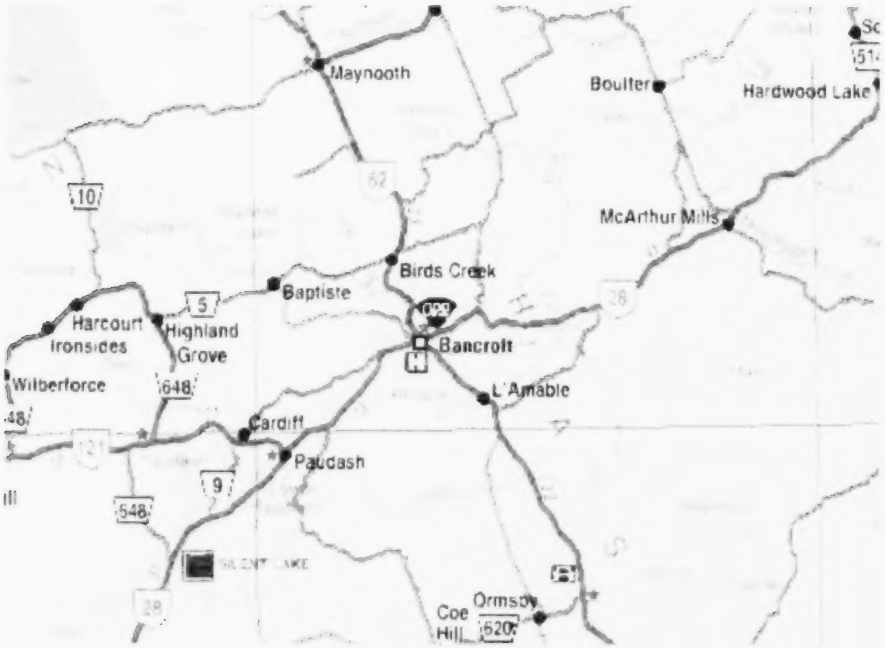

Figure 2 - Project Area

CONSULTANTS

The Base Mapping Company Ltd., of Ottawa, Ontario was awarded the pilot project on November 6, 2000 by the Geomatics Office, Ministry of Transportation under RFQ 9015-A-000130, GO Project Number 2000-661. The Base Mapping Company Ltd. acted as prime consultant providing project management, aerial triangulation, photogrammetric mapping and responsibility for final deliverables.

Sub-consultants on the project included:

- Richard Crouse & Associates of Fredrick, Maryland for provision of the aerial photography;
- Champlain Air Surveys, of Pembroke, Ontario for lab processing of the photography film; and
- Fairhall, Moffatt and Woodland Limited, of Ottawa, Ontario for provision of the ground control survey and targeting.

RECONNAISSANCE AND TARGETING

The consultants were required to establish appropriate horizontal and vertical photo control of sufficient accuracy to meet the aerial triangulation and DTM data collection specifications. The strict accuracy requirements of this project required a high-accuracy, homogeneous control network. The horizontal coordinate system was the 3-degree Modified Transverse Mercator (MTM) Ontario coordinate system based on the North American Datum 1983 (NAD83). The vertical datum was the Canadian Geodetic Vertical Datum 1928 (CGVD28, 1978 Southern Ontario Adjustment).

11 existing horizontal and six existing vertical control points formed the control framework from which photo control points would be coordinated.

Numerous photo control points were targeted before the aerial photography was flown. These were chosen in locations that would hopefully satisfy the photogrammetric requirements for 1:600 scale photography. Subsequent to the photography being flown, the targeted points and some additional photo-identifiable points were surveyed.

The consultants established photo control by painting crosses every 50 metres along the highway. These crosses were painted on the paved shoulder, alternating from one side to the other (i.e. there was a target on each side of the highway every 100 metres). In a few situations several targets in a row were painted on one side only, mainly for safety reasons. Each leg of the cross was 0.3 metres long and 0.08 metres wide. See Figure 3.

All horizontal control monuments were also targeted. The targets were made out of a hard material, white in colour, 0.3 metres square with a 0.08 metre square dark centre. These were set precisely over each monument using an optical plummet. When they were

lifted, their positions were confirmed using this same method. Additional targets were set laterally to the highway (wing points) at pre-selected locations. These targets were exactly the same as those used on the control monuments, unless a cross could be painted. To insure that the target was secure and would provide a good solid surface for an elevation, a 0.3 metre long, 0.036 metre square wood stake was driven flush with the ground. The target was nailed to this wood stake. These targets proved to be very good. See Figure 3.

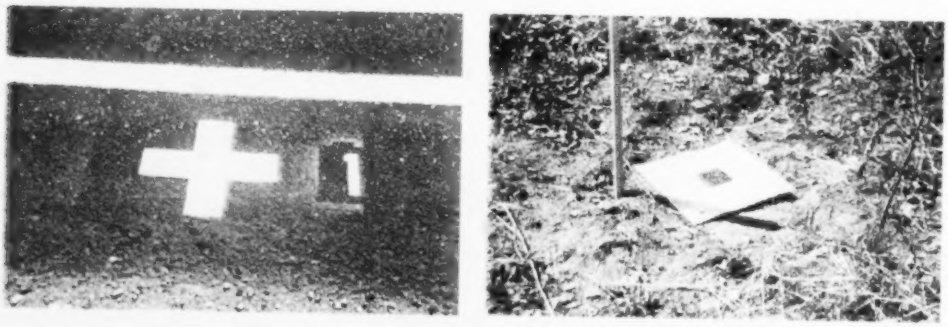

Figure 3 - Photo Control Targets

After the photography had been acquired, Base Mapping analyzed the control configuration. They made every effort to use the targeted points, but needed to choose some additional photo-identifiable points in order to satisfy the photogrammetric aerial triangulation requirements.

CONTROL SURVEY RESULTS

Vertical Control Results

With the exception of the targets set on the horizontal control monuments, all targets were leveled by using a Leica NA3000 digital level in combination with a Leica standard bar code staff. Levels were run up one side of the highway then down the other side, with frequent connections made to targets on the opposite side of the road.

All digital level data was downloaded and adjusted by the method of least squares. An unconstrained adjustment was performed holding one benchmark (00819728179) fixed. The results of this adjustment are summarized in Table 1.

Table 1 - Vertical control residuals from the unconstrained adjustment.

Benchmark	*Published Elevation (m)*	*Unconstrained Value (m)*	*Residual (m)*
0011920U335G	328.814	328.805	-0.009
0011979U228	326.675	326.663	-0.012

00819728177	329.778	329.769	-0.009
00819728179	334.132	-	-
00819728180	341.477	341.480	+0.003
00819728181	343.365	343.378	+0.013

The results indicated that a homogeneous vertical control network existed in the project area and to proceed with a fully constrained adjustment. The standard deviation of the final adjusted values ranged between 1mm and 2mm.

Horizontal Control Results

A combination of GPS and Total Station was used to survey the horizontal control. An unconstrained least squares adjustment was performed. The results are shown in Table 2.

Table 2 - Horizontal control residuals from the unconstrained adjustment.

Monument Number	*North Residual (m)*	*East Residual (m)*
00819880068	-0.025	-0.011
01019870414	+0.060	+0.077
01019870416	+0.057	+0.078
00819880064	+0.045	-0.097
00819880067	+0.004	+0.043
01019870412	+0.095	+0.002
00819880069	-0.016	-0.034
00819880070	-0.018	-0.056
01019870413	+0.085	+0.039
01019870419	-0.019	+0.043
01019870420	-0.039	+0.010

An analysis of the results indicated that the differences fell within 3rd-order accuracy criteria, however given the high accuracy requirements of the project, further refinement of the adjustment was attempted. A so-called "calibration" was performed, whereby the measured coordinates of the control points are compared to their corresponding published values and a four-parameter transformation is calculated between the two coordinate sets. A full calibration over the entire project area was carried out using all of the horizontal control monuments. Results of the full calibration were not satisfactory so the project was divided into two segments. One point (01019870413) had to be removed. Results of the calibrations are shown in Tables 3 and 4.

Table 3 - Calibration Results on Segment 1

Monuments Used	*North Residual (m)*	*East Residual (m)*
00819880064	-0.003	+0.006
01019870412	+0.016	-0.017
01019870414	-0.013	+0.011
	Scale Factor = 0.99999195	

	Rotation = 359° 59'46.0"	
Scale Factor Set to 1.0		
00819880064	+0.008	+0.002
01019870412	+0.014	-0.015
01019870414	-0.022	+0.013

Table 4 - Calibration Results on Segment 2

Monuments Used	***North Residual (m)***	***East Residual (m)***
01019870414	+0.004	-0.016
01019870416	+0.001	+0.020
00819880067	-0.002	+0.001
01019870419	+0.005	+0.009
00819880068	0.000	-0.002
00819880069	+0.006	-0.007
00819880070	-0.004	+0.005
01019870420	-0.010	-0.010
	Scale Factor = 0.99998953	
	Rotation = 0° 00'00.1"	
Scale Factor Set to 1.0		
01019870414	+0.027	-0.026
01019870416	+0.015	+0.009
00819880067	+0.004	+0.001
01019870419	+0.007	+0.017
00819880068	-0.009	+0.003
00819880069	-0.008	-0.005
00819880070	-0.026	+0.003
01019870420	-0.012	-0.002

The calibrations further improved the adjustment results. The subsequent aerial triangulation results proved that both the horizontal and vertical networks were sufficient to meet the accuracy requirements of the project.

AERIAL PHOTOGRAPHY

The purpose of the air photo mission was to obtain aerial photography at a scale suitable for photogrammetric measurements of hard surface ground features to an accuracy of ±20 mm. In order to obtain reliable measurements within the specified accuracy a photo scale of 1:600 was calculated.

Precise vertical aerial photography has been flown for decades using aerial cameras specifically designed to provide distortion free photo images. Aerial camera performance has been continually upgraded using state of the art technologies in electronics,

mechanical and optical fields. However aerial photography is usually flown at altitudes of 300 metres or more.

To achieve a photographic scale of 1:600 the photography had to be flown at an altitude of approximately 90 metres above mean ground elevation. As well, since the travel distance between consecutive exposure stations is only 55 metres for such large-scale photography, the aircraft must fly slow enough to allow the camera enough time to open and close it's shutter between each photograph.

A helicopter is capable of flying at such low altitudes while maintaining a slow, relatively stable, speed. Ideally the camera should be mounted inside, rather than outside, the aircraft as this configuration will eliminate camera air disturbances that could conceivably cause camera and image problems.

In the fall of 2000 there was no known firm in Canada with the required aerial equipment or experience for this project. After assessing various companies in the United States, the photo mission was subcontracted to Richard Crouse and Associates of Frederick, Maryland. Richard Crouse and Associates have the aircraft, camera equipment and qualified personnel for this type of project and have flown low-level helicopter photography for various projects throughout the United States.

A Leica RC20 aerial camera with FMC (forward motion compensation) and a distortion free 152 mm lens was used for this photo mission. FMC is essential in order to provide clear photo images at low altitudes since there is large relative camera motion. The camera was mounted in a Bell Jet Ranger 206B helicopter on a gyrostabilizer base to compensate for variations in aircraft orientation (typically referred as pitch, roll and drift), which are primarily caused by air turbulence (See Figure 4).

Permission to fly the aerial photography was provided by MTO in November of 2000. Unfortunately, due to early snowfalls and unsuitable weather conditions in the fall of 2000, the photography had to be postponed until spring of 2001.

The aerial photography was flown on May 3, 2001 after the targeting was put in place. The aerial photography was flown, as much as possible, in accordance with the "Vertical Aerial Photography Specifications, Version 3.5" (Ministry of Transportation Ontario, 2000a). However, as this was a pilot project there were some necessary variances to the specifications that were discussed and acknowledged by both MTO and Base Mapping.

The film was processed under Roll # 2000-1928, the camera focal length was 152.665mm and the average photo scale was 1:600. The photography consisted of 194 frames and 11 flight lines. The flight line configuration is shown in Appendix A.

Figure 4 - Helicopter and Aerial Camera Configuration

AERIAL TRIANGULATION

Aerial triangulation (AT) is carried out to provide sufficient horizontal and vertical control data within each pair of overlapping aerial photographs (stereo models). The ground surveyed horizontal and vertical control points are used to orient the stereo models in the mapping instruments and provide the appropriate horizontal and vertical datum for the measurement of the ground features and ground elevations. The AT process can be summarized as the photogrammetric densification of the ground control survey data throughout each pair of overlapping aerial photographs.

The key components of the AT process are photo preparation, mensuration and adjustment.

Photo preparation consists of the selection of the pass points between overlapping photographs, tie points between overlapping lines of photography and identification of the ground surveyed horizontal and vertical control points. The pass and tie point locations are marked on the photo contact prints and appropriately coded. These points are selected along the fiducial lines of the photograph and are generally located in clear, unobscured, relatively level ground areas.

The precise locations of these photogrammetric control points (pass and tie points) are marked on the diapositive (positive transparency produced from film negative) by viewing the point location in stereo and marking it with a small 60um circle. The instrument utilized for this process was a KERN PSM2 point transfer device.

The mensuration of the pass, tie and control points was carried out on a first order analytical Wild BC2 stereo plotter. ABC TRI software was used to measure and record the points and fiducial mark locations. The measured values were output in a PAT B format. The instrument calibration was checked and confirmed as acceptable before and after the mensuration.

Upon completion of the mensuration process all points were adjusted by least squares using K-Block software. Published coordinates of the horizontal and vertical ground control were held fixed and the adjustment was reviewed to ensure the specified accuracies were achieved. Points with residuals beyond the specified accuracies were re-measured in the BC2 and re-adjusted.

The RMS values and largest residuals for the pass points, tie points and control points were reviewed and it was confirmed that the aerial triangulation adjustment satisfied the "Specifications for Aerial Triangulation, Version 1.2" (Ministry of Transportation Ontario, 1995). For 1:600 photography, the specifications call for pass and tie point accuracy of RMSx = RMSy = 0.006m, RMSz = 0.012m and control point accuracy of RMSx = RMSy = 0.009m, RMSz = 0.015m. A summary of the AT adjustment results are given in Tables 5 and 6.

Table 5 – Point Count and RMS Values from Constrained AT Adjustment.

Point Type	*Nx*	*Ny*	*Nz*	*RMS x (m)*	*RMS y (m)*	*RMS z (m)*
Pass Points	1482	1482	1482	.003	.002	.005
Tie Points	202	202	202	.004	.004	.005
Pass & Tie	1684	1684	1684	.003	.002	.005
Control Points	117	117	266	.006	.006	.005

Table 6 – Largest Residuals from the Constrained AT Adjustment.

Point Type	*R x (microns)*	*R y (microns)*	*R z (microns)*
Pass & Tie	-25	24	-31
Control Points	27	29	-31

The adjusted photogrammetric control values were used as photogrammetric control for the mapping process.

PHOTOGRAMMETRIC MAPPING

The photogrammetric data collection was performed according to the " Photogrammetric Surveys Digital Terrain Model Data Capture and Processing Guide, Version 1.6" (Ministry of Transportation Ontario, 1994). As previously mentioned, for 1:600 scale photography, the required accuracy for hard surface features is 0.018m and the required accuracy for soft surface features is 0.045m.

The large-scale photography permitted collection of numerous features not normally mapped from the traditional 1:3000 photography. Team members from the Ministry of Transportation and Base Mapping discussed how to collect and code all reliable data visible on the 1:600 scale photography. It was decided that the "Field Code Feature Sketches for MTO Engineering Surveys" (Ministry of Transportation Ontario, 2000b) would be followed. This specification is normally reserved for ground surveys only but it was easily adaptable to this pilot project.

Features such as ditch inlets, gas valves, water valves, hydro wires, and utility markers were clearly visible in the 1:600 photography. Variations of less than two centimetres in the pavement elevation could be recorded, permitting accurate mapping of the crown of the highway. Curbs could be collected with three strings (back top of curb, front top of curb, edge of gutter) as in ground surveys. Usually curbs are generated features based on standard sizes when mapping from 1:3000 photography.

Typical point spacing along a feature was one to three metres and adjacent strings were generally two to three metres apart. Thus a very dense grid of points was used to create the digital terrain models. The point and string spacing far exceeded that which is normally collected during a ground survey.

Within the area the planimetric information could be described as urban to mixed urban/rural. The topography was generally moderate to steep relief with numerous rock cuts. Rock cuts adjacent to the highway made it difficult to map some areas to the desired specifications. Note the rock cuts to the east of the highway, as evidenced by the contour lines shown in Appendix A. The major contour interval (blue lines) is 50 metres.

Once again, as this was a pilot project, Base Mapping tried three types of photogrammetric mapping equipment to help form an opinion as to the type that would be best utilized for the data collection:

- digitally equipped analogue stereo plotters – Wild A10 and Wild AMH (first order instruments);
- analytical equipment – Wild BC2;
- softcopy photogrammetric technology – LH Systems.

All three types of photogrammetric equipment provided stereo viewing of the photogrammetric models. However, in some situations where the pitch, roll and drift of the photograph were excessive, the digitally equipped analogue stereo plotters could not be used. Models that could not be set up on these instruments were set up on the analytical or softcopy photogrammetric equipment.

The RMS results of the stereo models set up for the data collection were recorded on individual data sheets. In general, the average recorded discrepancies of the photogrammetric pass points, tie points and horizontal and vertical control points used were in the $\pm$4 to 7 mm range. The setup discrepancies of the control were acceptable for the desired mapping results of 30 microns or better.

There were 155 stereo models in the project area. Each model covers an area of about 55 metres along the highway by 100 metres wide. The project area was divided into 15 segments, each containing about 10 stereo models. Each segment contains 25,000 to 50,000 collected data points. Approximately 36.5 hectares were mapped. Segment files were delivered to the MTO Geomatics Office for further processing, quality control, DTM creation and final drawing production. The final AutoCad project files were then delivered to MTO Eastern Region Geomatics Section.

Note: Much of this section of the report was derived from the "Report to Ministry of Transportation for Large Scale Photogrammetric Mapping" submitted as the final report for RFQ No. 9015-A-000130, GO No. 2000-661 (The Base Mapping Company Limited, 2001).

Audit Survey

The intent of the project was to achieve MTO ground survey accuracy requirements (i.e. 2 cm on hard surfaces) from airborne methods. Thus an accurate ground survey was required to assess the accuracy of the photogrammetric mapping. Accordingly, MTO field crews carried out an extensive audit survey. See Figure 5. Total station and level were used to achieve better than 2-centimetre accuracy.

The same existing horizontal and vertical control and targeted photo control were used to control the audit survey. To remain consistent with the photogrammetric data, coordinate values for the photo control were taken from the aerial triangulation adjustment. Some additional traverse points were established for field data collection.

The control traverse from the audit survey was adjusted by least squares, holding all existing and targeted control point coordinates fixed. No major discrepancies were revealed, thus verifying the results of the AT and confirming that an accurate control framework existed in the project area.

Detailed audit surveys were done about every kilometre. The audit areas were about 200m in length and 30m wide. In each audit area, a total station ground survey was conducted to collect topographic detail that would be most useful for accuracy comparisons.

Well-defined hard surface features, such as centreline, edge of pavement, crown of road, curbs, gutters, sidewalks, concrete structures, catch basins and manholes would be used for the primary accuracy comparisons. A five-metre spacing of feature points was implemented, instead of the normal 25-metre spacing, to provide a dense grid of points similar to that of the photogrammetric data.

Soft surface features were surveyed at five to ten-metre spacing, rather than the normal 25-metre spacing. Collected features included original ground strings, top and bottom of ditches, top and bottom of earth cuts and gravel surfaces.

In addition to the detailed audit surveys, a complete centreline profile was collected at approximate 25-metre point spacing. This proved to be invaluable for accuracy assessment since it provided audit data throughout the entire project.

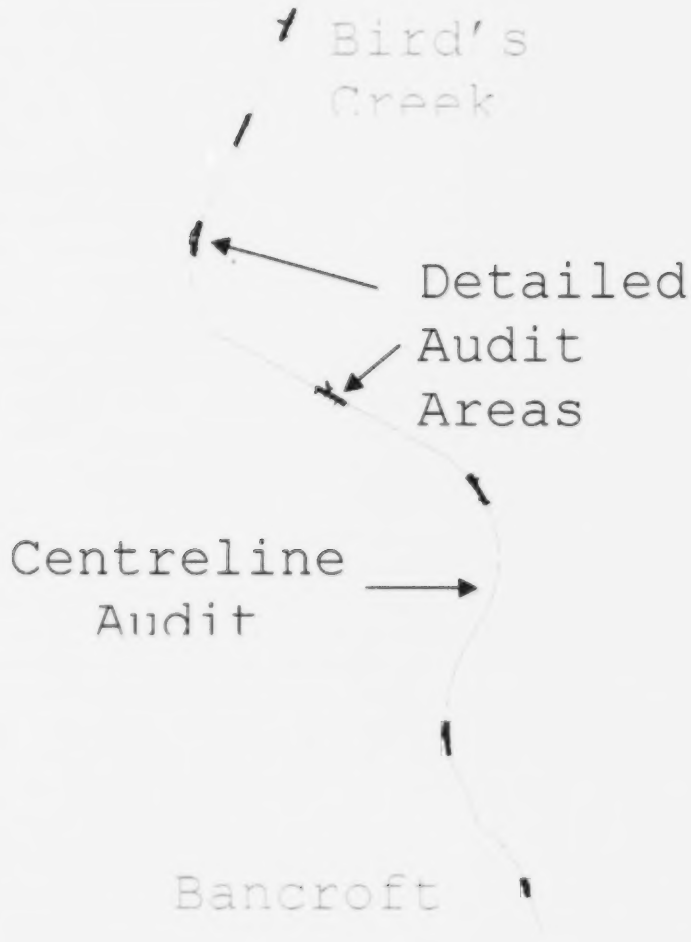

Figure 5 - Audit Survey

Accuracy Comparisons

MTO has developed customized quality assurance routines that run inside of AutoCad and Land Development Desktop. These customized routines were used to compare the audit survey to the photogrammetric mapping. The accuracy of the mapping was determined by considering the audit survey as the "ground truth".

The routines are designed to perform various comparisons:

- Compare the elevation of audit points to the elevation of the DTM generated from the original survey, at the same (x,y) location as the audit point.
- Search within a one-metre radius of the audit point for features collected in the original survey. Compare the (x,y,z) of the audit point to the (x,y,z) of the feature point. In the case of a line feature passing within one metre, the audit point will be compared to an interpolated point along the line feature that lies perpendicular to the audit point as measured along the line feature.

In the first case, comparisons are made to the DTM of the original survey at the audit point location. In the second case, the comparisons are made at the location of the feature, which is likely at a different (x,y) than the audit point. This second method will also compare any feature passing within one metre of the audit point. This can result in comparisons to features different from the audit feature, which are invalid for accuracy assessment. Due to difficulties in sorting this information, the following data is based on the first analysis method only. The first method provides the best data for vertical accuracy assessment.

Audit data were sorted into the following categories based on the collected features:

1. Centreline shots - the centreline (painted line) of the traveled pavement surface
2. All hard surfaces - features such as centerline, crown, paved surfaces, sidewalks, curbs, concrete structures, manholes, catch basins
3. Ground shots - shots on natural ground
4. Drainage features - bottom of ditch and ditch centreline.

The following figures show both a scatter plot and frequency distribution of the elevation differences between audit survey (ground survey) and photogrammetric DTM (helicopter DTM) for each feature category.

NOTE: In the frequency distribution charts, each bar represents the number of elevation differences in the range from the previous to the current value along the y-axis i.e. in Figure 6 there are 80 comparisons in the range -0.005 to 0 m and 91 comparisons in the range 0 to 0.005 m.

Figures 6 and 7 show the results of elevation differences for centreline shots. This data

provides the best information to derive a realistic estimate of the accuracy of the helicopter mapping data. The audit points are spread throughout the complete project, providing multiple checks on the photogrammetric DTM in all 155 stereo models (see Figure 5). The centreline feature is easy to identify on a two-lane highway. Formation of the DTM takes into account adjacent features, in this case asphalt shots on either side of the centreline.

The centreline data yielded 534 comparisons, with a mean of 0.001m and a standard deviation of 0.014m. The minimum and maximum elevation differences were -0.057m and 0.056m respectively. Figure 7 shows that 50% of the comparisons are less than zero. 86% of the elevation differences are within ± 0.02 m and 96% are within ± 0.03 m. The kurtosis indicates a slightly peaked distribution and the skewness indicates a slightly positive asymmetry. Overall the statistics illustrate that the normal distribution is the acceptable probability model for the data.

(Kurtosis characterizes the relative peakedness or flatness of a distribution compared to the normal distribution. Positive kurtosis indicates a relatively peaked distribution. Negative kurtosis indicates a relatively flat distribution. Skewness characterizes the degree of asymmetry of the distribution around its mean. Positive skewness indicates a distribution with an asymmetric tail extending toward more positive values. Negative skewness indicates a distribution with an asymmetric tail extending toward more negative values).

The standard deviation represents the area under the normal distribution curve that contains approximately 68% of the total area. In other words, the probability is 68% that a measurement will fall between $\mu \pm \sigma$, where μ is the mean and σ is the standard deviation. For the centreline shot data there is 68% probability of the elevation differences falling between 0.001 ± 0.014 metres.

Multiples of the standard deviation are used to represent various probability levels. The 95% probability, or 95% confidence level, is commonly used in surveying. For a single random variable the 95% confidence level is given by $\mu \pm 1.96\sigma$. For the centreline shot data there is 95% probability of the elevation differences falling in the range 0.001± 1.96(0.014) m or -0.026 m to 0.028 m.

Accuracy is influenced by both the random error component of a measurement and by uncorrected systematic bias. If there is no bias in the measurements then any measurement of precision (such as the standard deviation) is also a measure of accuracy (Mikhail and Gracie, 1981). Given that the mean of the centreline shot data is almost zero (no bias), and assuming that the ground survey data represents the "truth", it can be concluded that the resulting standard deviation is a true measure of the accuracy of the photogrammetric mapping.

Figures 8 and 9 show the elevation differences for all hard surfaces captured in the audit

survey, including the centerline shots. Again the distribution is normal with a mean of -0.001 m, standard deviation of 0.017 m and 54% of the values less than zero. 82% of the elevation differences are within ± 0.02 m and 93% are within ± 0.03 m. The 95% confidence level of the elevation differences is -0.001± 1.96(0.017) or -0.034 m to 0.032 m.

Figures 10 and 11 show the elevation differences for ground shots. These measurements have a negative bias as indicated by the mean of -0.032 m. This is typical for grass and vegetation-covered surfaces. The photogrammetrist cannot see through the vegetation and will read the elevation higher than the true ground level, whereas during a ground survey the prism pole can be placed directly on the ground through the vegetation. In spite of this shortcoming of photogrammetric mapping, and considering the variability of the natural ground surface, the results for the ground shots are impressive. 90% of the elevation differences are within ± 0.1 m and 99% are within ± 0.2 m. The 95% confidence level of the elevation differences is -0.032± 1.96(0.064) or -0.157 m to 0.093 m.

Lastly, figures 12 and 13 show the elevation differences for the bottom of ditches. Similar to ground shots, the presence of water and vegetation in the ditches will be problematic for photogrammetric mapping. The results are still reasonable with 80% of the elevation differences within ± 0.1 m and 96% within ± 0.2 m. The 95% confidence level of the elevation differences is -0.069± 1.96(0.054) or -0.175 m to 0.037 m.

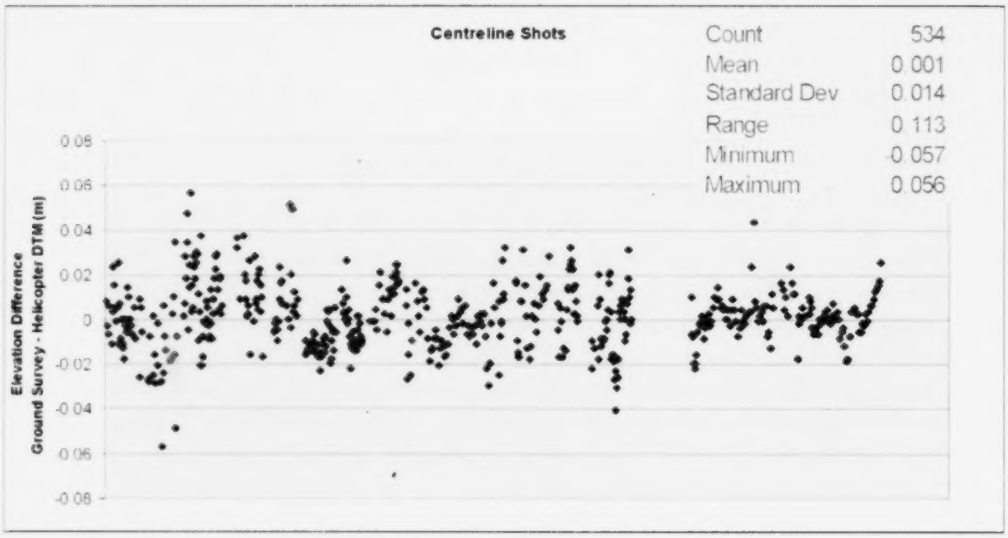

Figure 6 – Elevation Differences on Centreline Shots

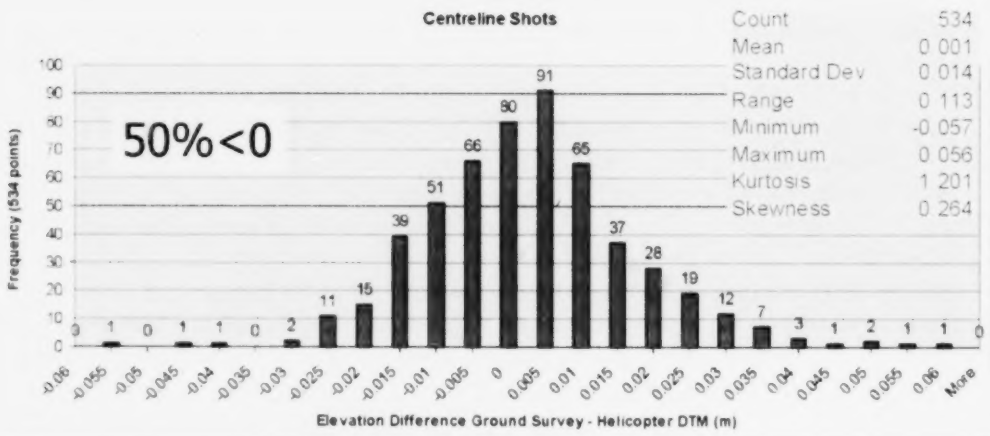

Figure 7 – Frequency Distribution of Centreline Shot Elevation Differences

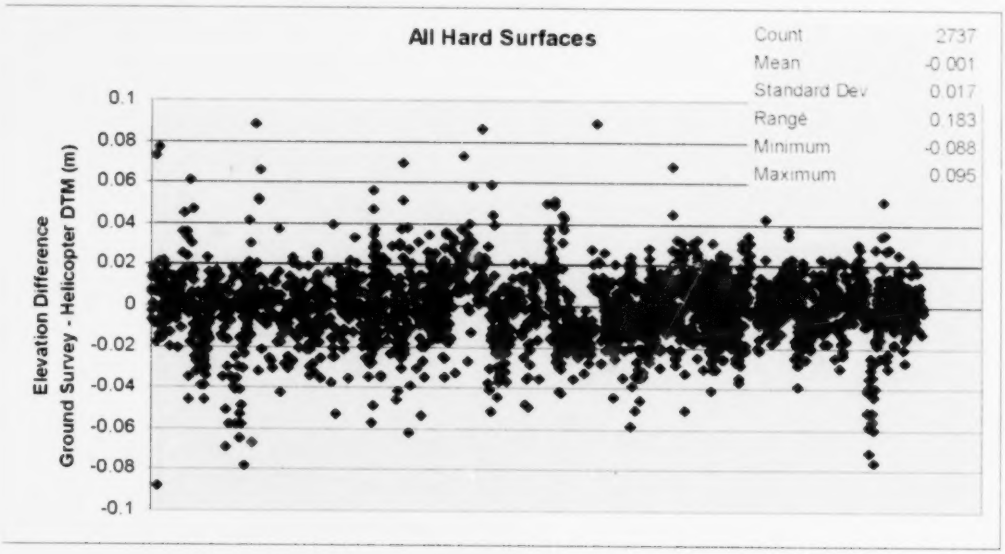

Figure 8 – Elevation Differences on Hard Surface Features

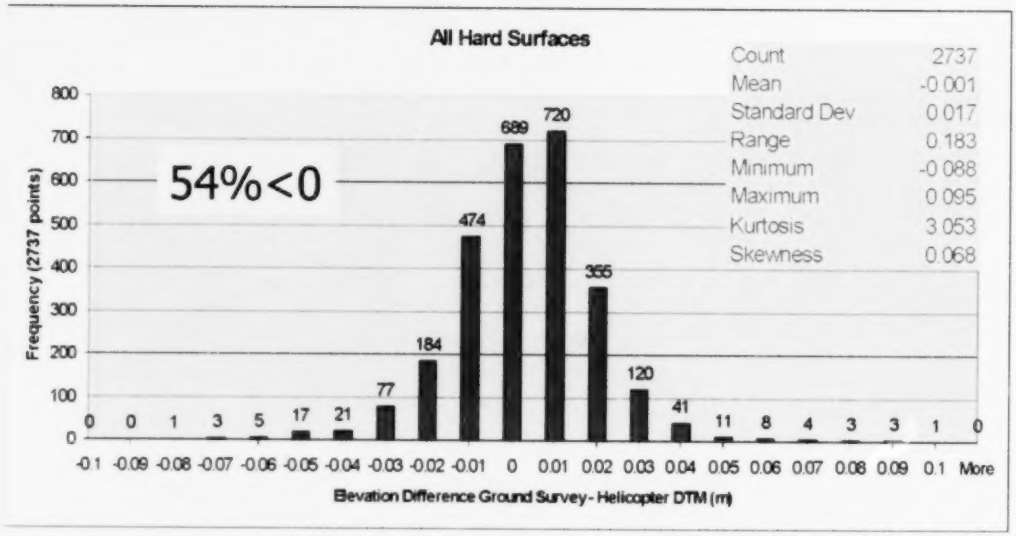

Figure 9 – Frequency Distribution of Hard Surface Elevation Differences

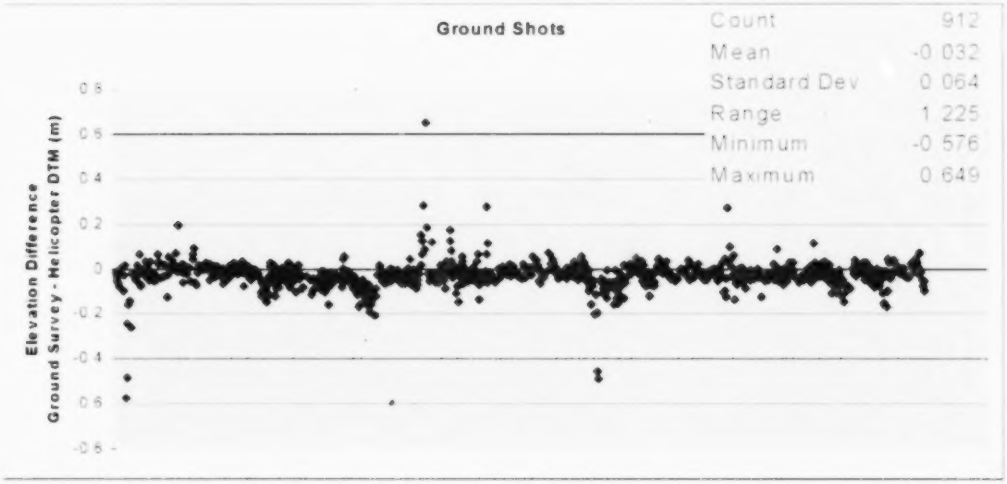

Figure 10 – Elevation Differences on Ground Shots

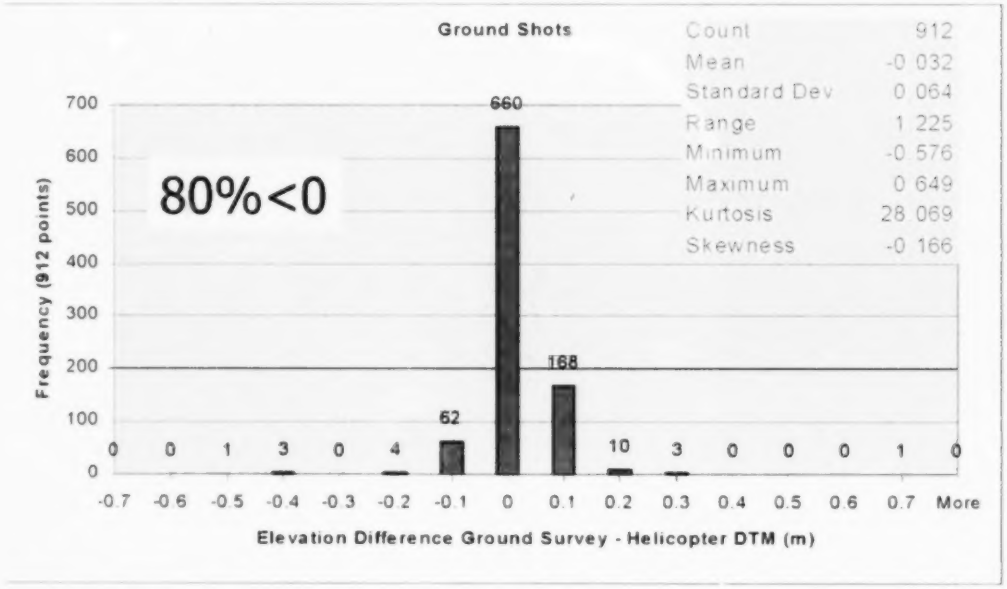
Ground Shots
Count 912
Mean -0 032
Standard Dev 0 064
Range 1 225
Minimum -0 576
Maximum 0 649
Kurtosis 28 069
Skewness -0 166
80%<0
Frequency (912 points)
660
168
62
0 0 1 3 0 4 10 3 0 0 0 1 0
-0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 More
Elevation Difference Ground Survey - Helicopter DTM (m)

Figure 11 – Frequency Distribution of Ground Shot Elevation Differences

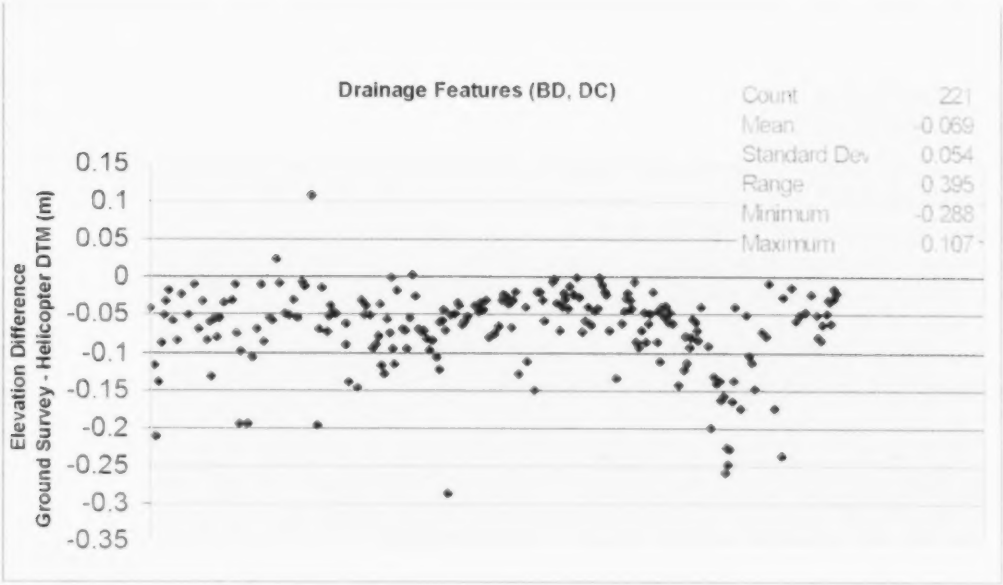

Figure 12 – Elevation Differences on Drainage Features

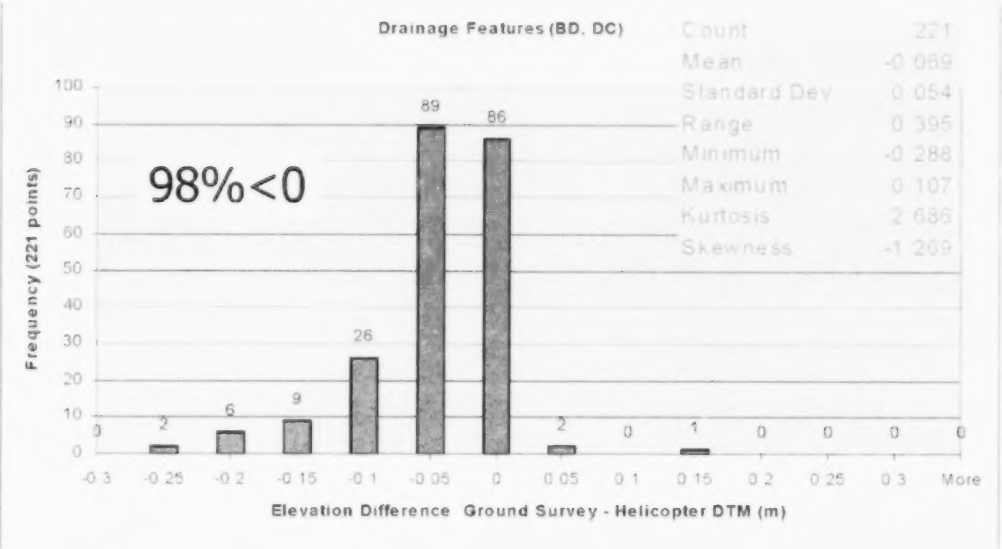

Figure 13 – Frequency Distribution of Drainage Elevation Differences

Analysis of the Helicopter Method

The accuracy of photogrammetric mapping from the large-scale photography collected by helicopter for this pilot project has proven to be comparable to total station ground survey accuracy. Accordingly the high accuracy photogrammetric mapping will primarily be compared to total station ground survey techniques. A few other emerging technologies will also be noted.

BENEFITS OF HELICOPTER METHOD

High accuracy photogrammetric mapping has several benefits over ground survey methods:

- Data collection from photogrammetry is more efficient. Many more data points can be collected in less time. Point and string spacing can be reduced to the metre level and still be more efficient than ground survey collection at 25 m spacing.
- The increased data density results in a superior DTM, given that the collected data is of similar accuracy.
- After ground control is established all remaining data collection is done remotely without ground contact, making the survey safer for field crews and the motoring public.
- Ground control can be placed safely away from the traveled lanes.
- Photogrammetric data collection causes no traffic disruption.
- There is no need to go on traveled lanes to collect pavement features.
- Data can be collected in areas that have restricted or unsafe ground access, such as interchanges, ramps, bridges, busy highways, environmentally or politically sensitive areas. Also note that on major highways in the Greater Toronto Area, ground survey data is usually not collected between the edges of pavement (i.e. no crown data is collected) due to safety and traffic concerns.
- More data can be collected at a later time, without returning to the field, if needed.
- A permanent photographic record is available.

DRAWBACKS OF HELICOPTER METHOD

Some drawbacks of high accuracy photogrammetric mapping versus ground survey methods include:

- More ground control is required. For high accuracy, vertical ground control should be established in every model i.e. every 50 metres for 1:600 scale aerial photography. Control is placed every 250 metres on a typical MTO total station ground survey.

- Some ground survey work may still be required for certain features not visible in the photography, such as culvert inverts, culvert sizes, bottom of ditches (when filled with water), bridge clearances, critical areas obscured by vegetation, legal survey monuments.
- Possibly higher survey cost, depending on the size and location of the project. See "Cost Comparison" below.

COMPARISON TO ALTERNATE SURVEY TECHNIQUES

Aside from conventional total station ground surveying, other survey techniques should be considered for comparison:

1. Reflectorless total station - Accuracy of pavement shots has proven to be similar to conventional total station accuracy when site distances are kept short i.e. 50 metres or less (Lamb, 2000). Accordingly, more control is required. Instrument setup locations must be optimized so that the angle of incidence of the laser light beam with the pavement is not too small. Typically this will require setup on the shoulder and closure of one lane of traffic as per Ontario Traffic Manual procedures (Ministry Of Transportation, 2001). However the pavement shots can be collected remotely without a surveyor walking onto the traveled lanes.
2. Terrestrial Lidar (LIght Detection And Ranging) scanner – Setup requirements are similar to reflectorless total station. Added features include the ability to scan a dense grid of points automatically and view a digital intensity image of the survey area. A digital camera is also integrated into the system. The accuracy and feasibility of this method has not yet been tested in detail at MTO.
3. Conventional photogrammetric mapping - Aerial photography is normally captured at a scale of 1:3000 or 1:2400 from fixed-wing aircraft. Resulting accuracy on hard surfaces is 7 to 10 centimetres, which is well above the 2-centimetre MTO requirement for highway design.
4. Airborne Lidar - The accuracy of airborne lidar has proven to be no better than 15 centimetres on hard surfaces (Berg and Ferguson, 2001). Again, this not accurate enough for MTO highway design requirements.
5. Mobile mapping vehicles such as MTO's ARAN - MTO's ARAN vehicles are currently used for pavement condition analysis. Data is collected as the vehicle moves at highway speeds. A video log is also recorded. Sensors on the rut bar are very accurate relative to one another and can detect small variations in pavement elevation. However there continue to be practical problems with positioning the sensors to achieve 2-centimetre accuracy relative to ground control. The Geomatics Office continues to follow developments in this area.

Methods 3,4 and 5 are not accurate enough to be considered further at this time. Methods 1 and 2 improve upon conventional total station surveys because data can be gathered remotely without entering live traffic lanes. However theses methods are still ground-based. Any of the safety and traffic restrictions of a conventional total station instrument

setup apply equally to these methods. They would likely require setup on the shoulder to properly "see" the pavement area. Thus lane closures and the use of blocker trucks are not eliminated, and workers are still exposed to traffic hazards.

COST COMPARISON

The cost breakdown for the pilot project is as follows:

Aerial photography	$28,500
Ground control survey	$11,000
Aerial triangulation	$ 5,280
Photogrammetric data collection	$31,000
Total	$75,780

Note that the aerial photography is 38% of the total cost. The high cost is partly due to the fact that the flying firm is located in Maryland, USA. The photography would likely have been one-third to one-half the cost if an Ontario firm could be used for this phase of the project.

An estimate was prepared by MTO Eastern Region Geomatics section to survey the same area by total station. The estimate included everything from project preparation through to creation of the final Autocad drawings and DTM's. The estimate considered that the photogrammetric mapping covered a 50m strip centered on the highway and that certain features (legal survey monuments, culvert inverts) were not collected in the mapping.

Estimated costs were broken down as follows:

Project preparation	$ 2,900
Field operations	$31,740
Office operations	$ 8,600
Total	$43,240

The estimated ground survey cost is 57% of the mapping cost. Several points must be considered when comparing these costs:

- The photogrammetric data was collected at a much greater density. Normal ground survey data collection intervals are 10 - 25 metres. To ground survey at the same density as the mapping would increase the cost significantly, perhaps by an additional 30% to the field operations.
- The pilot project was conducted in an area where blocker trucks are not required for surveying the traveled highway lanes. On major highways, traffic control is necessary and expensive. Blocker trucks cost $1,000 - $1,500 per day, thus doubling the field survey cost each day a blocker truck is needed.
- Ground survey work is logistically more difficult and less efficient in heavy traffic areas.
- The cost of the helicopter aerial photography will be relatively high until this service can be obtained within Ontario.

It is expected that the cost of helicopter mapping will be more competitive on major highways where traffic control and safety issues heavily impact the cost and efficiency of ground surveys.

Conclusions

The pilot project has proven that photogrammetric mapping from 1:600 scale aerial photography can provide high accuracy data collection suitable for highway design purposes. There does not appear to be any limitation to hard surface feature collection, other than the fact that the feature must be visible in the photography. The accuracy achieved on hard surfaces is comparable to that of conventional ground surveys.

Due to grass and vegetation cover, soft surface feature collection from photogrammetric mapping is generally less accurate than from ground surveying. However the results achieved here still meet MTO's engineering survey requirements for most soft surface features since photography was flown in early May when vegetation was low. To achieve the highest accuracy in any aerial photography campaign, photography should be flown in the spring or fall when vegetation cover is minimal.

Features not visible in the photography must be ground surveyed. Examples include culvert inverts, culvert sizes, bottom of ditches, bridge clearances, survey monuments, and critical areas obscured by vegetation, water or man-made objects. Thus some ground survey work will still be required to supplement the photogrammetric mapping.

The photogrammetric mapping process allows for efficient collection of far more data than would be collected by ground survey. Numerous points can be measured quickly. Point density can be increased or decreased at any time, depending on the requirements for the feature being measured. Overall, a better digital terrain model is formed since more data points are used.

Once the ground control is surveyed all remaining data collection is done in the office. Field crews are not subjected to dangerous situations in heavy traffic. High accuracy mapping reduces the need for expensive traffic protection measures such as lane closures and use of blocker trucks, and minimzes field crew exposure near heavy traffic, thereby providing for a safer, more efficient way of collecting critical pavement data.

Although the cost of high accuracy photogrammetric mapping may be greater than ground surveying, other factors must be considered in the cost-benefit analysis. A better DTM will improve design and save construction costs by reducing overruns. Data can be collected in areas not normally accessible or safe for ground surveying. Safety of surveyors is improved since most data collection can be performed away from live traffic. Traffic control costs are reduced, and the motoring public benefits from fewer lane closures and traffic disruptions.

Recommendations

Conduct a second project on a major highway corridor using this methodology.

Encourage the private sector to establish capabilities for acquisition of low altitude aerial photography, by helicopter or other aircraft.

Consider high accuracy photogrammetric mapping as a viable survey option under one or more of the following circumstances:

- field crews would be at risk to carry out ground survey operations safely;
- major traffic control and lane closures would be required for ground surveys;
- minimal traffic disruption is required;
- the project area is inaccessible or impractical to survey by ground methods i.e. ramps, interchanges, multi-level structures, bridges;
- the project area has severe survey restrictions imposed i.e. surveying is only allowed at night or on weekends;
- pavement data collected by ground survey is not sufficient to produce an accurate digital terrain model i.e. no survey data is collected between the edges of pavement, thus the crown elevation and crossfall must be estimated;
- a dense digital terrain model is required on the hard surfaces;
- it is cost-effective.

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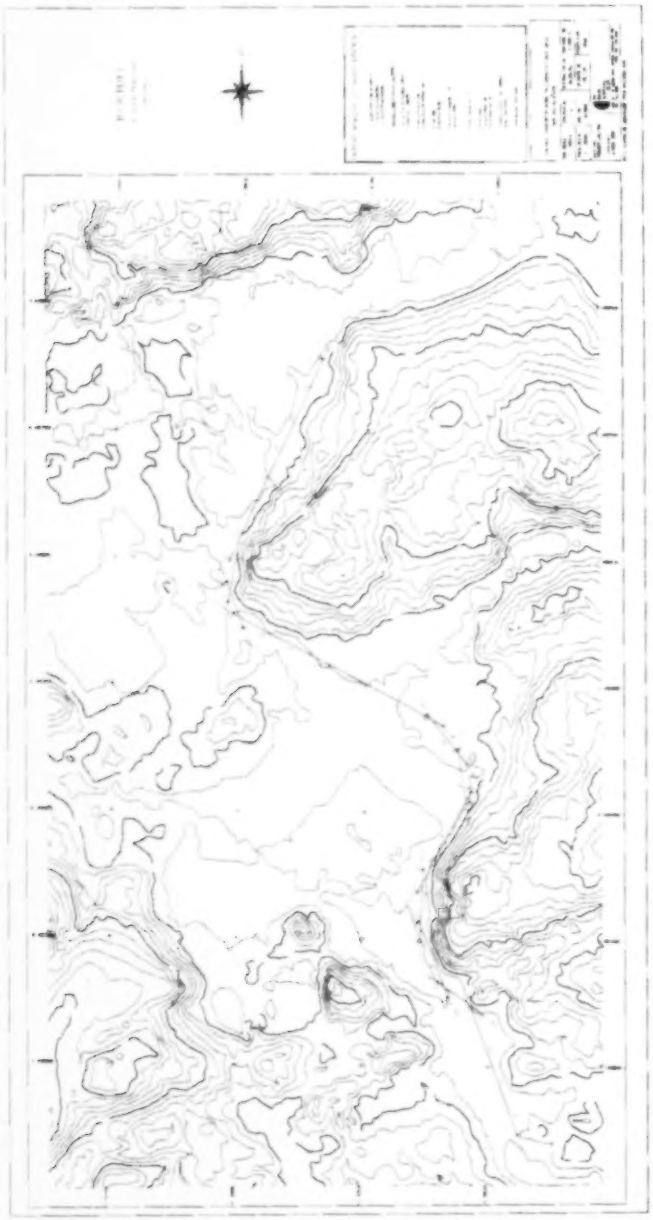
Appendix A – Flight Line Configuration



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